

**A FUNDAMENTAL RHEOLOGICAL STUDY OF THE
BLADE COATING PROCESS**

Project 3069

**Report Four
A Progress Report
to
MEMBERS OF GROUP PROJECT 3069**

March 21, 1977

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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A FUNDAMENTAL RHEOLOGICAL STUDY OF THE BLADE COATING PROCESS

SUMMARY

This report covers extensive use of the IPC Rheometer to evaluate coatings. Limited success was obtained with a ring type of geometry due to unstable operation, and this type of geometry is considered infeasible with the machine as presently constructed.

Extensive testing of dilatant coatings showed that at the higher shear rates reached in the Rheometer, the dilatancy changed to Newtonian or even shear thinning behavior. This suggests that such coatings could be used to increase coat weight without either changing machine conditions or increasing coating handling problems.

Results obtained with polyvinyl alcohol (PVA) coatings were comparable to those found earlier. The tests confirmed that lower molecular weight PVA behaves much like starch binders in flow properties. Mixtures of low and medium molecular weight binders indicated that undue viscoelastic properties did not occur and that such mixtures might be used as sole binders in coatings.

INTRODUCTION

This report brings Project 3069 to a close. In large part the original goals of the research have been achieved. Considerable progress has been made in describing the nature of the flow in blade nips under the severe conditions existing on blade coating machines. A machine has been made available for the realistic testing of coating rheology. The results are, to a greater extent than desired, of an empirical nature, but this does not greatly diminish their utility.

For "regular" coating mixtures* which have monotonically changing viscosities and no appreciable viscoelastic behavior, the IPC Rheometer has been useful for establishing that the simple behavior extends to shear rates of 10^6 sec^{-1} , the range of typical coater operation. Maximum utility of the instrument may result, however, when considering unusual coating rheology, e.g., systems exhibiting viscoelasticity or dilatancy. Although further work is necessary to define the limits of operation with such materials and to clarify the interpretation of the results, the studies to date have shown promise in evaluating those materials under conditions comparable to commercial high speed coating.

The body of this report is divided into three sections dealing with three types of coatings. The utility of the ring-blade geometry for "regular" starch/clay coating mixtures is shown first. This is followed by a study of the effects of molecular weight on the viscoelastic behavior of polyvinyl alcohol/clay coating mixtures. Finally, the rheological properties of a series of dilatant coating mixtures comprised of starch/SBR latex binder and clay pigment are examined.

*Throughout this report the words "coating mixture" will be abbreviated to coating. This term refers to the pigment-adhesive formulation and not to a coating on paper or other substrate.

EXPERIMENTAL

PREPARATION OF THE COATING MIXTURES

Materials Used

Pigment: KCS [Spray Dried (S.D.)] clay, density 2.6
Dispersant: Quadrafos (0.1% based on clay) (sodium tetraphosphate)
Binders: Stayco M Starch, density 1.5
Dow 636, SBR, latex (48% solids), density solid latex 1.05
Polyvinyl alcohol, medium molecular weight [Degree of Polymerization (D.P. approx. 1800)], Air Products Grade 125
Polyvinyl alcohol, low molecular weight (D.P. approx. 700),
Air Products Grade 107
Defoamer and antishock agent: Air Products Surfynol 104-A, 0.06% based on clay, used with polyvinyl alcohol binder

Procedure

Starch binders were prepared by cooking in a stainless steel beaker for 15 minutes with a steam injector to a maximum temperature of 95°C. The solids level at the start of the cook was 39% and was somewhat greater after the cook due to evaporation. The final solids were adjusted to 39% solids or less with additional water.

The latex binder was used as received.

The polyvinyl alcohol (PVA) was slurried in water while stirring. The 125 grade was prepared at 7.23% solids and the 107 grade was prepared at 21.1% solids. The mixtures were heated to 90°C and stirred for 15 minutes. Heat was supplied by a steam coil in a water bath. The Surfynol was added and the mixing was continued for another five minutes. The solutions were cooled in the water bath with cold water in the coil. Sufficient water was added to make up any loss by evaporation.

Clay slips were prepared in a Hobart mixer, Model N50. Mixing was done at low speed (No. 1) using the wire whip. The same conditions were used for making up

the coatings as well. The clay slips were prepared at 75% solids and were mixed for 30 minutes. For the PVA coatings the slips were diluted to 71% solids and mixing was continued for another 20 minutes. For the other coatings the slips were used at 75% solids.

For the PVA coatings the clay slip was added to the binder in the Hobart mixer while mixing. The rate of addition was slow and there was no sign of shock. For the other coatings the binder and water were added to the clay slip while mixing. For all coatings the mixing was continued for 30 minutes after combining all constituents. The compositions of the several coatings are presented in Table I.

TABLE I

COATING COMPOSITIONS

| Binder | Coating No. | Solids, % | Binder/Pigment Ratio | |
|-----------------------|-------------|-----------|----------------------|--------------------|
| Starch | 1 | 55.0 | 0.200 | |
| | 2 | 60.0 | 0.200 | |
| Polyvinyl Alcohol | | | | Grade 125: |
| | | | | Grade 107 |
| | 3 | 49.8 | 0.050 | 1:0 |
| | 4 | 51.7 | 0.080 | 1:1.4 |
| | 5 | 53.4 | 0.110 | 1:5.6 |
| | 6 | 55.0 | 0.140 | 0:1 |
| Starch plus SBR Latex | | | | Latex in Binder, % |
| | 7 | 59.8 | 0.200 | 0 |
| | 8 | 62.8 | 0.192 | 34.6 |
| | 9 | 66.3 | 0.186 | 68.0 |
| | 10 | 67.9 | 0.185 | 68.1 |
| | 11 | 68.4 | 0.182 | 84.2 |
| | 12 | 68.5 | 0.180 | 100.0 |
| | 13 | 68.9 | 0.180 | 100.0 |

TESTING PROCEDURES

IPC Rheometer

The details of the instrument and its operation were described in Progress Report Three of this project dated May 16, 1975. The coating evaluation is done in several runs. With the rotational speed ω as a parameter, the normal force F is set as the independent variable, and the resulting torque T and gap Δ are measured as the dependent variables.

It was desirable to measure the viscoelastic normal forces, and another geometry for the shear plate was devised to accomplish this. This ring-blade configuration is shown in Fig. 1. It is a modification of the earlier ring-blade design (Fig. 7, Progress Report Three) with additional gaps in the ring to decrease the tilt problem described on page 17 of Progress Report Three.

The ten degree blade shear plate (Fig. 11, page 22, Progress Report Three) was used to gather the bulk of the data in the present report.

Hercules Viscometer

Hercules rheograms were obtained using established procedures. Sometimes the flow in the Hercules instrument became unstable, resulting in violent chatter on the recording chart caused by a "stick-slip" phenomenon of the coating in the annulus. The reason for this is not certain but it may be a cavitation problem. There is evidence that when it happens the "down" portion of the rheogram is altered irreversibly. As common practice it is considered best when instability occurs to repeat the rheogram and start the "down" curve just before the instability occurs.

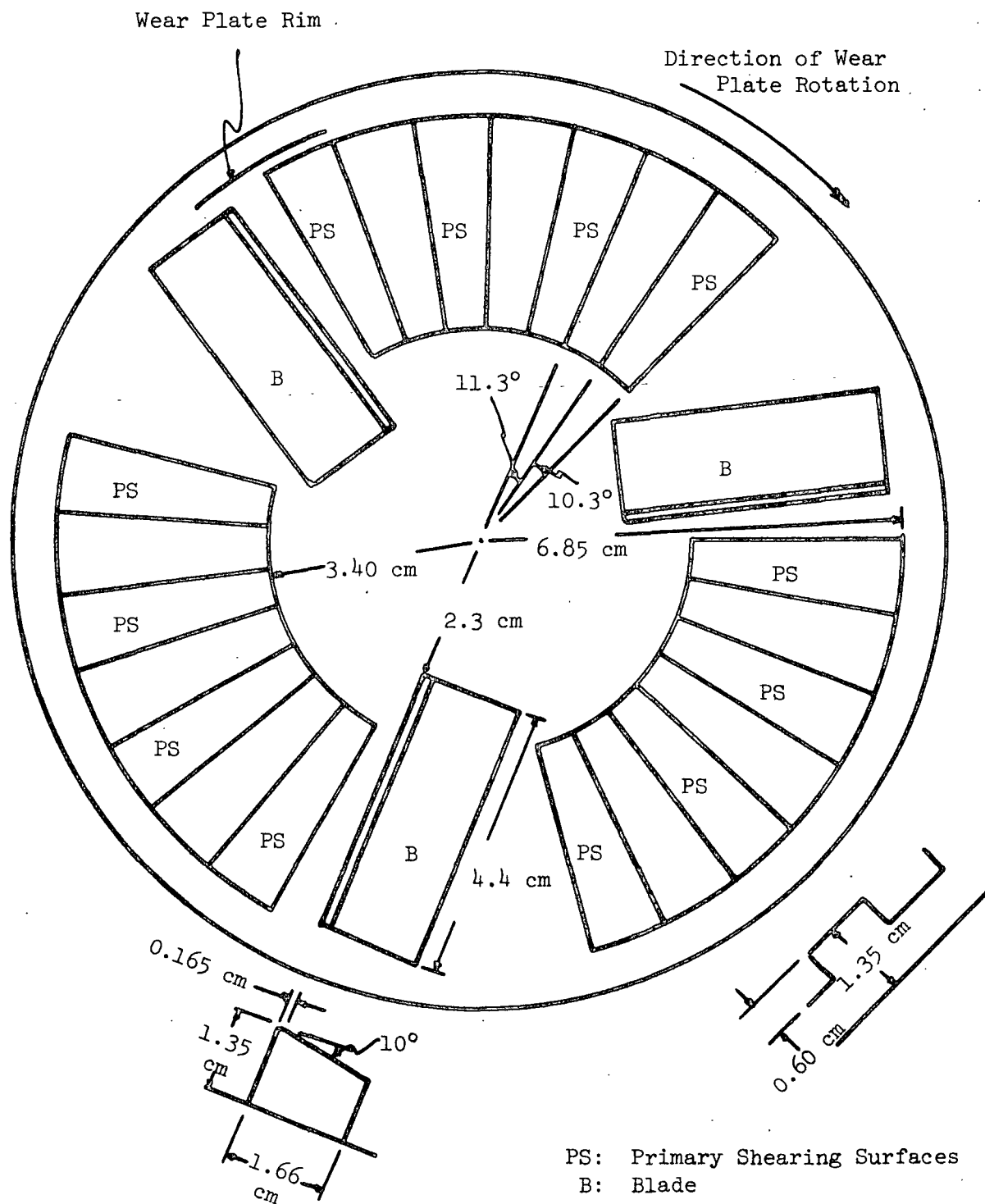


Figure 1. Ring-blade Shear Plate

Some data were taken at constant rotation speed of the viscometer.

To do this the speed is set by running up or down to the desired value with the controls on semiautomatic, and the drive is stopped. The coating is put into the cup and the usual preparation is made for a rheogram. When the on button is pushed, the speed will immediately jump to the value previously set. Values of torque are marked on the chart paper as a function of time. The accuracy at the shorter times is poor. Generally this procedure requires two persons, one to note the indicated time and the other to mark the chart.

RESULTS OBTAINED WITH THE RING-BLADE GEOMETRY

The ring-blade shear plate described in the Experimental Section (see Fig. 1) was constructed in an attempt to improve the tilt problem mentioned earlier. In principle, the greater the number of ring sections for a given total angle of ring section, the less the tilt effect. Later calculations have shown that even this geometry probably does not provide adequate control of film thickness and tilt angle. The data obtained are presumed to be reliable measures of fluid viscosity.

The only successful use of the ring-blade geometry occurred when starch based coatings were tested. Results obtained with the ring-blade and the ten degree blade geometries are presented in Fig. 2 and 3. Here, values for the viscosity η (\underline{T}) and η (\underline{F}) are plotted against shear rate. They have been calculated from the measured torques and normal forces, respectively, using the theory described previously which assumes viscometric flow (Progress Reports Two, page 24 and Three, page 28). The agreement between the results from the two geometries is good. While the shear rate range covered was fairly limited, the results do confirm what has been presumed before (1-3), that flow of the starch type coatings in ten degree blades is approximately viscometric and the blade geometry gives an acceptable measure of viscosity.

It is unfortunate that the use of the ring-blade geometry with the more interesting viscoelastic coatings (polyvinyl alcohol binders) was unsuccessful.

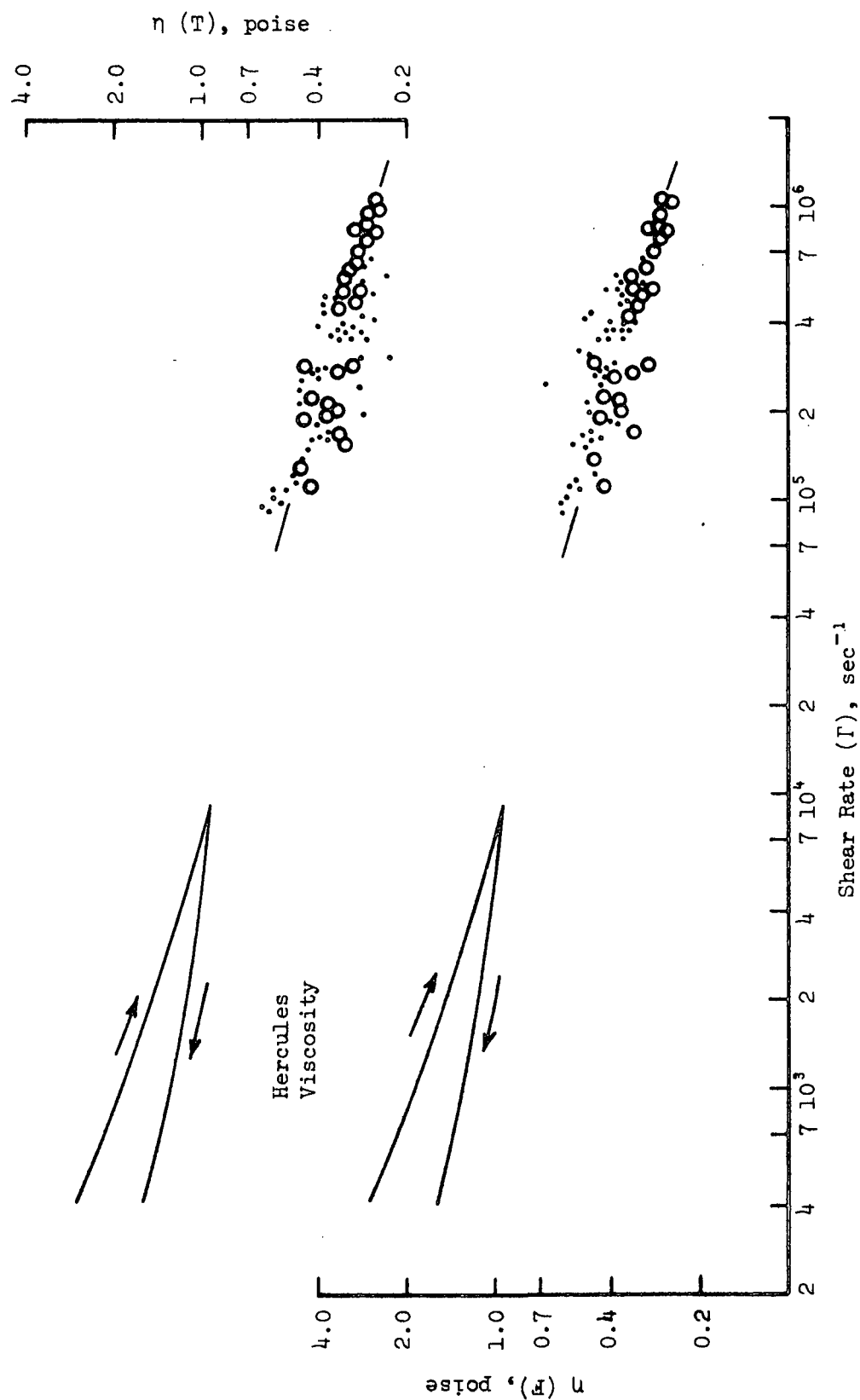


Figure 2. Viscosity Data for Coating No. 1. Filled Circles, Blade Geometry; Open Circles, Ring-blade Geometry. 25°C

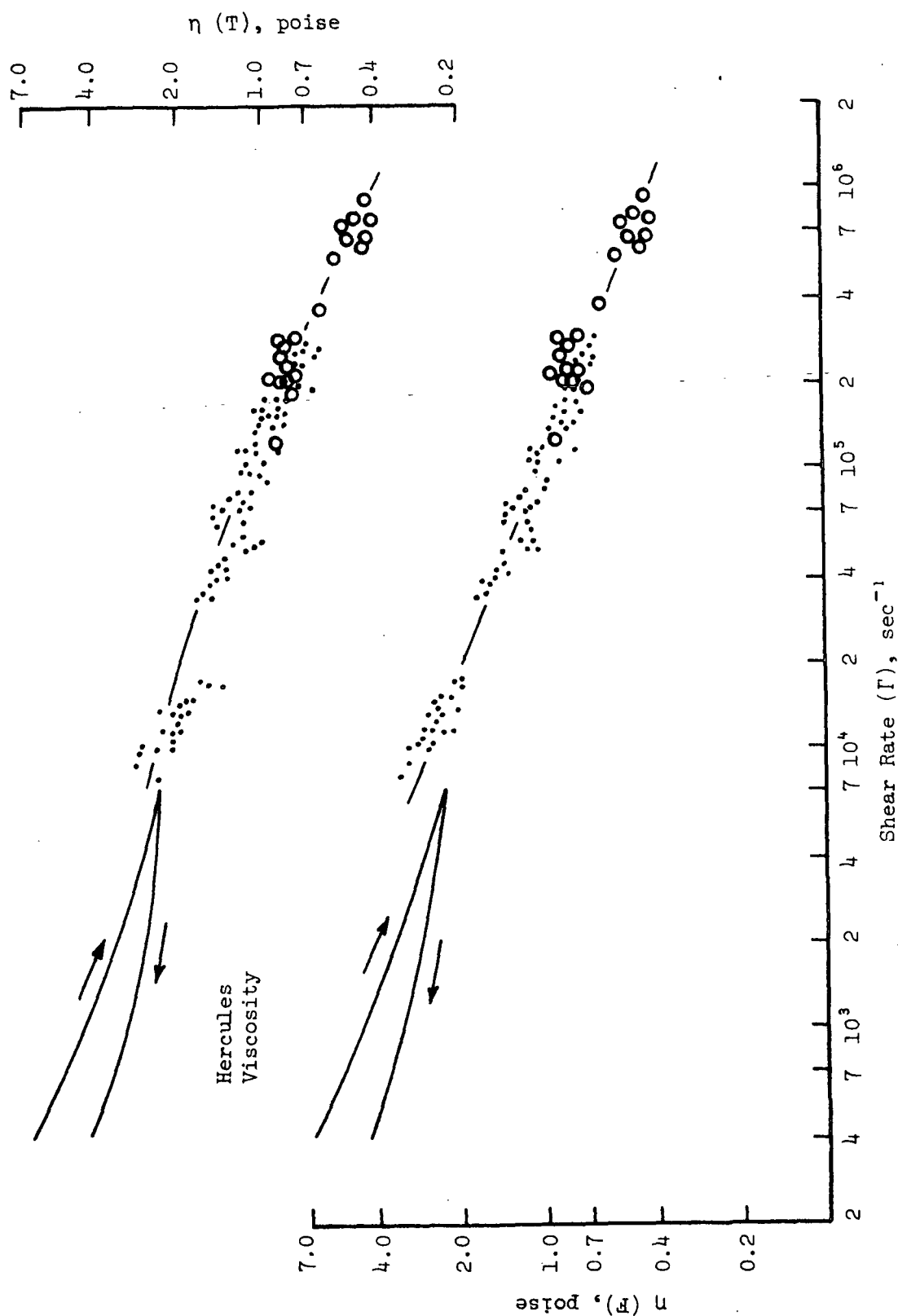


Figure 3. Viscosity Data for Coating No. 2. Filled Circles, Blade Geometry; Open Circles, Ring-blade Geometry. 25°C

TEST RESULTS OBTAINED ON POLYVINYL ALCOHOL COATINGS

High molecular weight polyvinyl alcohol (PVA-H) has been known to produce "poor rheology" in paper coatings. This behavior has been considered dilatancy on blade coating machines (4). Based on extensive investigations reported previously (1-3), it is known that the reason for the unique behavior of PVAH is viscoelasticity, not dilatancy. Further, it has been shown that this is a property not detectable with common test instruments (e.g., the Hercules Viscometer), but becomes quite evident in tests in the blade nip geometry.

The most recent tests on PVA, which are presented in this report, were undertaken for two reasons: (1) Miller and Kennedy (5) reported that PVA operates satisfactorily on blade coaters if the molecular weight (MW) is sufficiently low. The present tests were undertaken to determine whether such low MW material gives blade nip results comparable to "regular" or "well behaved" starch type coatings in contrast to the usually viscoelastic behavior found with higher MW material. (2) Coatings with mixtures of medium and low molecular weight PVA were tested to determine to what extent higher MW binder might produce "poor rheology" in such combinations.

The results of these tests are presented in Fig. 4-7. Figure 4 contains results for medium MW binder (Air Products Grade 125, Coating No. 3), Fig. 7 for low MW binder (Air Products Grade 107, Coating No. 6). The coatings 4 and 5 (Fig. 5 and 6) are mixtures of coatings 3 and 6 in ratios 2/1 and 1/2, respectively. The binder-pigment ratios of No. 3 and 6 (see Table I) are those which would produce satisfactory pigment binding (5). Although the same may not be true for coatings 4 and 5, the binder level would probably be at least close to that required for satisfactory coatings.

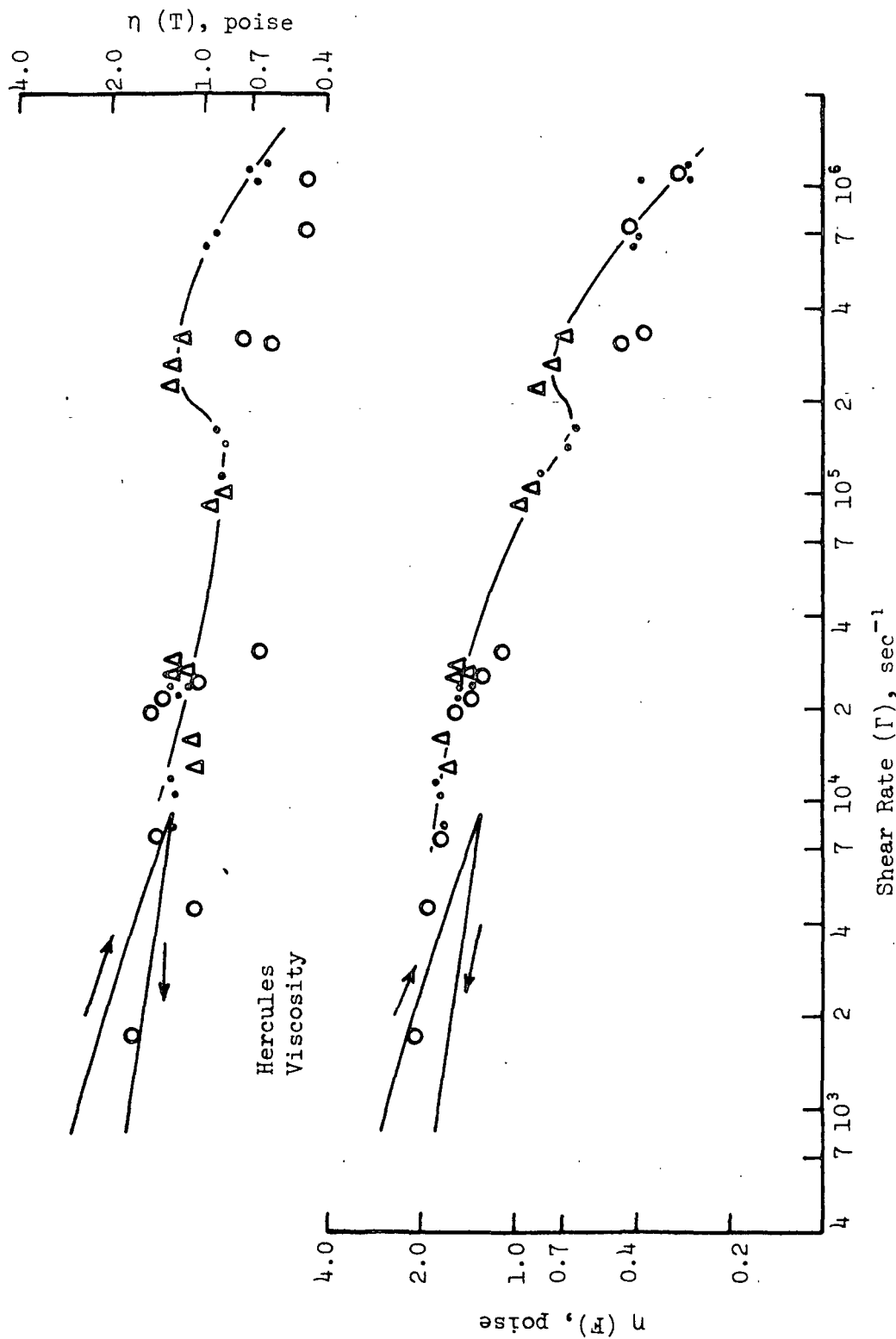


Figure 4. Viscosity Data for Coating No. 3. Symbols Correspond to Different Angular Velocities. Open Circles, <50 ; Filled Circles, 50-100; Triangles, >100 Rad/sec. 28°C .

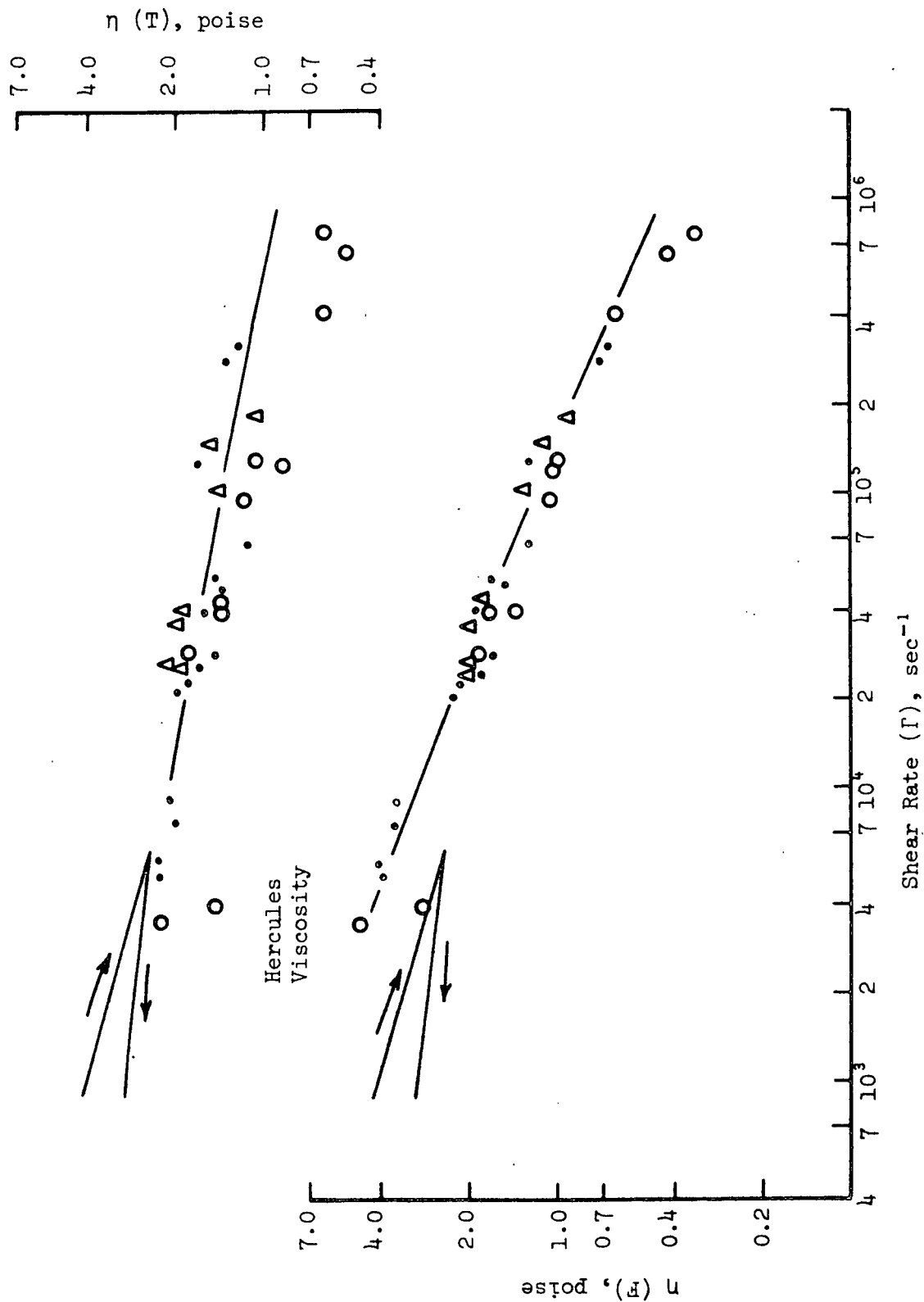


Figure 5. Viscosity Data for Coating No. 4. Key to Symbols Same as Fig. 4. 28°C

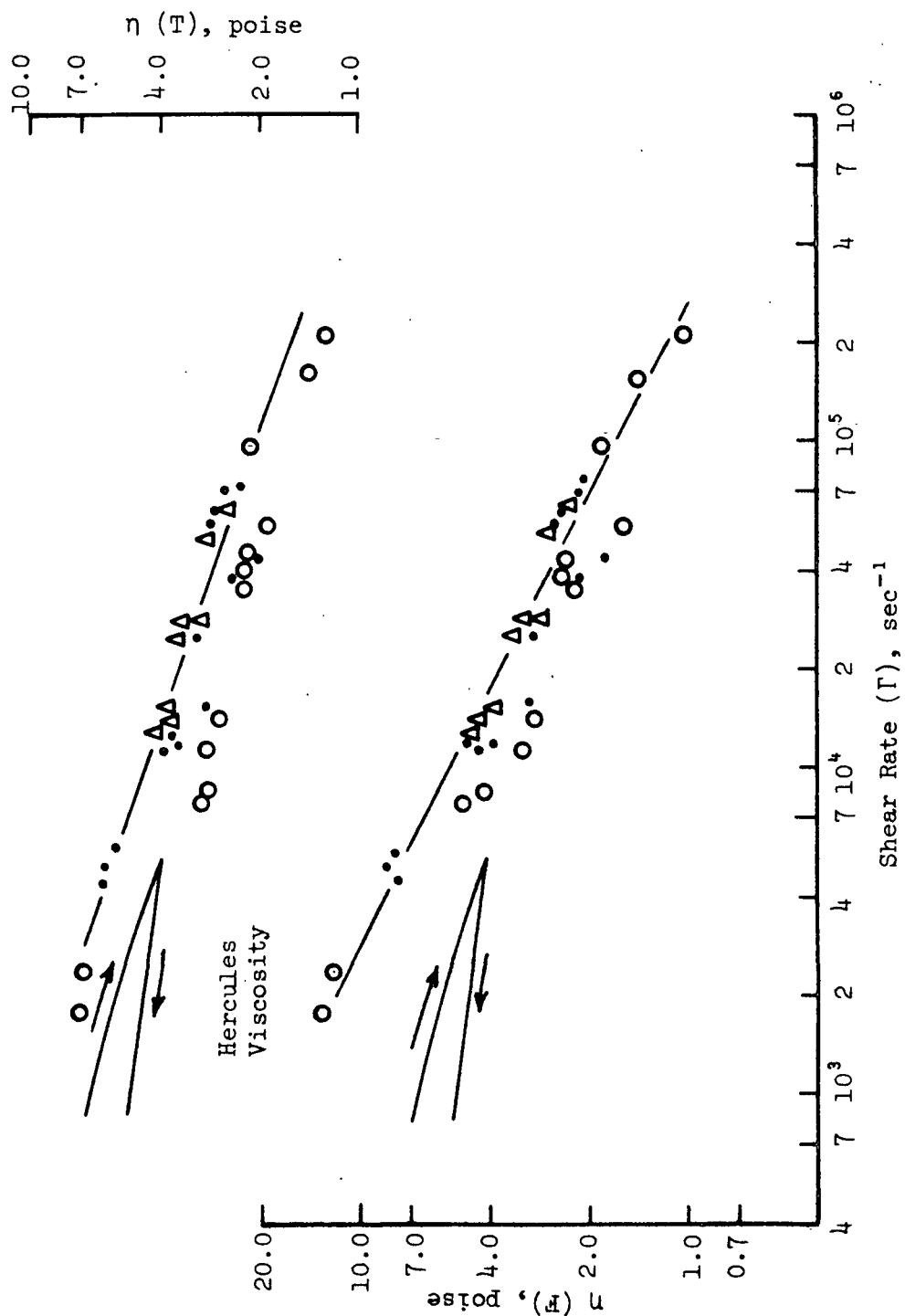


Figure 6. Viscosity Data for Coating No. 5. Key to Symbols Same as Fig. 4. 28°C

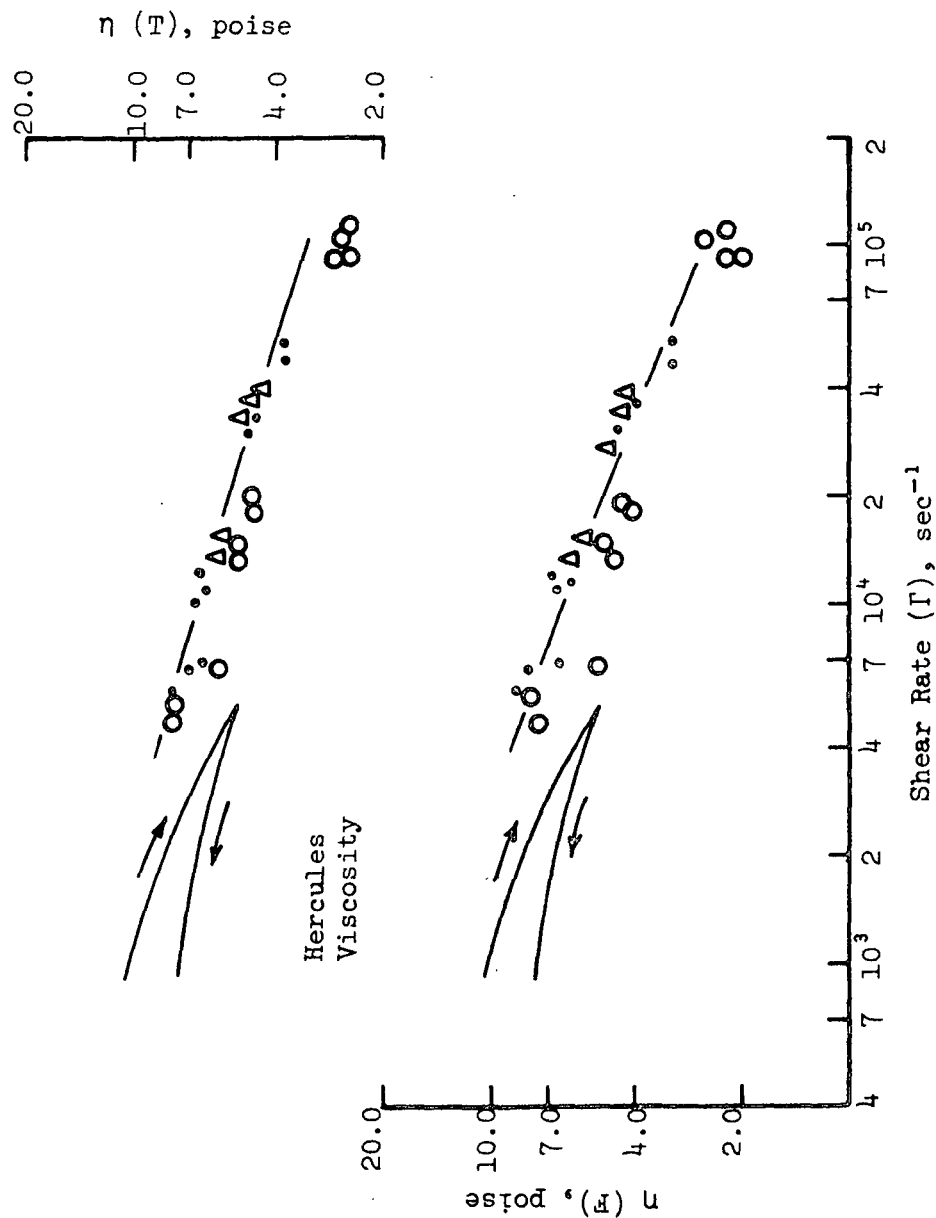


Figure 7. Viscosity Data for Coating No. 6. Key to Symbols Same as Fig. 4. 28°C

From the results it is seen that there is some evidence that IPC Rheometer viscosities are lower when determined at lower rotational speeds (<50 radians/sec) or (rad/sec), especially with the more viscoelastic coatings. This was found to be even more characteristic of highly dilatant coatings described elsewhere in the report. It is apparent that for these coatings the lack of common curves at all speeds is due to the inadequacy of the viscometric flow theory used in calculating the reported viscosity results. The results are true viscosities only to the extent that the viscometric flow theory is valid. This may well explain why coating No. 3 would appear to be dilatant on blade coaters but not in common viscometer tests. Probably the best approach in analyzing results of this nature is to disregard low speed results (<50 rad/sec) since such rotational speeds represent lineal velocities much lower than is common to coaters (e.g., 50 rad/sec would represent a lineal speed of about 300-700 ft/min).

The coating containing the higher molecular weight binder (Fig. 4) exhibits the minimum and maximum in the viscosity at high shear rates that has previously (1-3) been associated with the presence of viscoelasticity in these systems. Compare particularly the present results with those of Fig. 20, Progress Report One for "Coating 5" and "Fluid 21" obtained on the Blade Nip Rheometer. These formulations, while not identical, were comprised of a polyvinyl alcohol of similar molecular weight at similar binder to pigment ratios and percent solids. The same features are apparent in the data from both instruments and have previously been implicated (1-3) as the reason such coatings have been termed "dilatant" in the mill.

The coating prepared using the lower molecular weight PVA yields well-behaved "starchlike" results (Fig. 7) out to a shear rate of 10^5 sec^{-1} . Unfortunately data are not available for this coating in the shear rate range 10^5 - 10^6 sec^{-1} where

viscoelastic behavior is found for the higher molecular weight binder (Fig. 4).

Miller and Kennedy (5) reported streaking and "dilatancy" with a binder of moderate molecular weight, but no such problems with one of lower molecular weight. These results are in accord with both theory and experiment with regard to the viscoelastic properties of polymer solutions (6); the elastic properties of the latter increase strongly with increasing molecular weight. The mixtures (Coating No. 4 and 5) show a gradual change from their components (Coating No. 3 and 6) without undue viscoelastic contribution by the higher molecular weight PVA of Coating No. 3. In agreement with previous work (5) this suggests that a judicious mixture of binders (low plus medium molecular weight PVA) might produce satisfactory coatings without the "poor rheology" characteristic of highly viscoelastic binders.

RESULTS OBTAINED ON DILATANT COATINGS

THE HERCULES RHEOGRAMS

A series of seven coatings was tested, with the relative amounts of latex and starch in the binders and the percentage solids of the coatings being varied. The Hercules rheograms (Fig. 8-14) show a gradual variation from routine shear thinning in Fig. 8 to extreme dilatancy in Fig. 14. The progression to dilatancy corresponds approximately with the increase in solid volume fraction in the coatings, i.e., the volume fraction of pigment plus latex particles.

The dilatant coatings are characterized by rheogram loops which are the reverse of the usual thixotropic loops. In Fig. 10 and 11 it may be observed that the approach to dilatancy is signaled by the loop before a noticeable increase in viscosity with shear rate increase is apparent. In Fig. 12 and 13 there seems to be both thixotropic and dilatant loops for the same coating. Probably measurements which extend to much lower shear rates would show this to be the general case for dilatant coatings.

THE IPC RHEOMETER RESULTS

The rheometer results in Fig. 8-14 are presented as viscosity functions. In transforming experimental data to viscosity values it is assumed that the flow in the blade nip is viscometric. Evidence has been presented before to support this assumption for coatings with starch binders (Progress Report One). As the coatings become more dilatant it is seen that the assumption must be invalid to some extent since the results for low speed and high speed (the open and closed symbols, respectively) diverge greatly. One factor responsible for this might be that a power law exponent is assumed for the viscosity at shear rates which vary

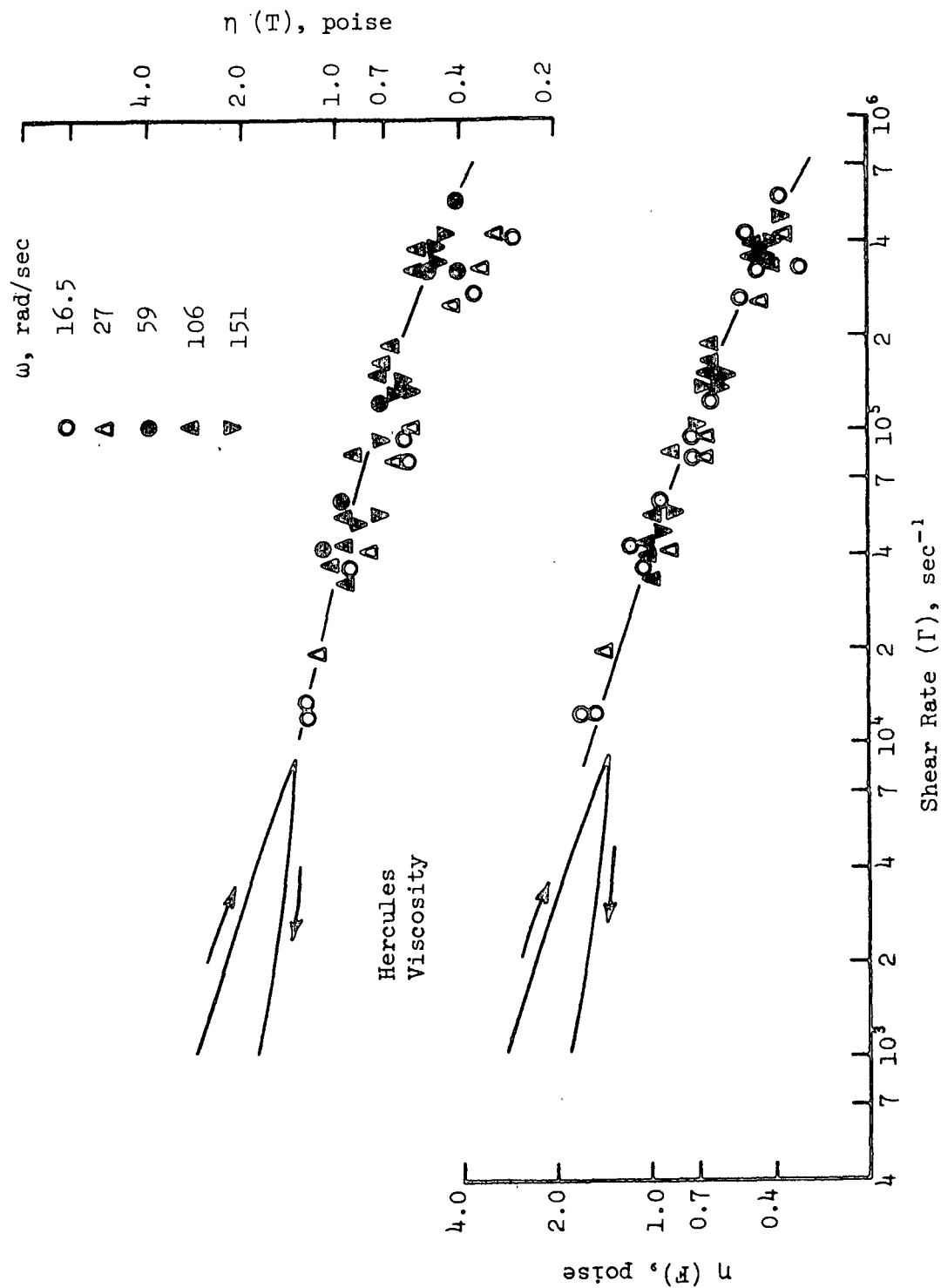


Figure 8. Viscosity Data for Coating No. 7. Different Symbols Correspond to the Indicated Angular Velocities. Volume Fraction of Clay Plus Latex: 0.291. 35°C

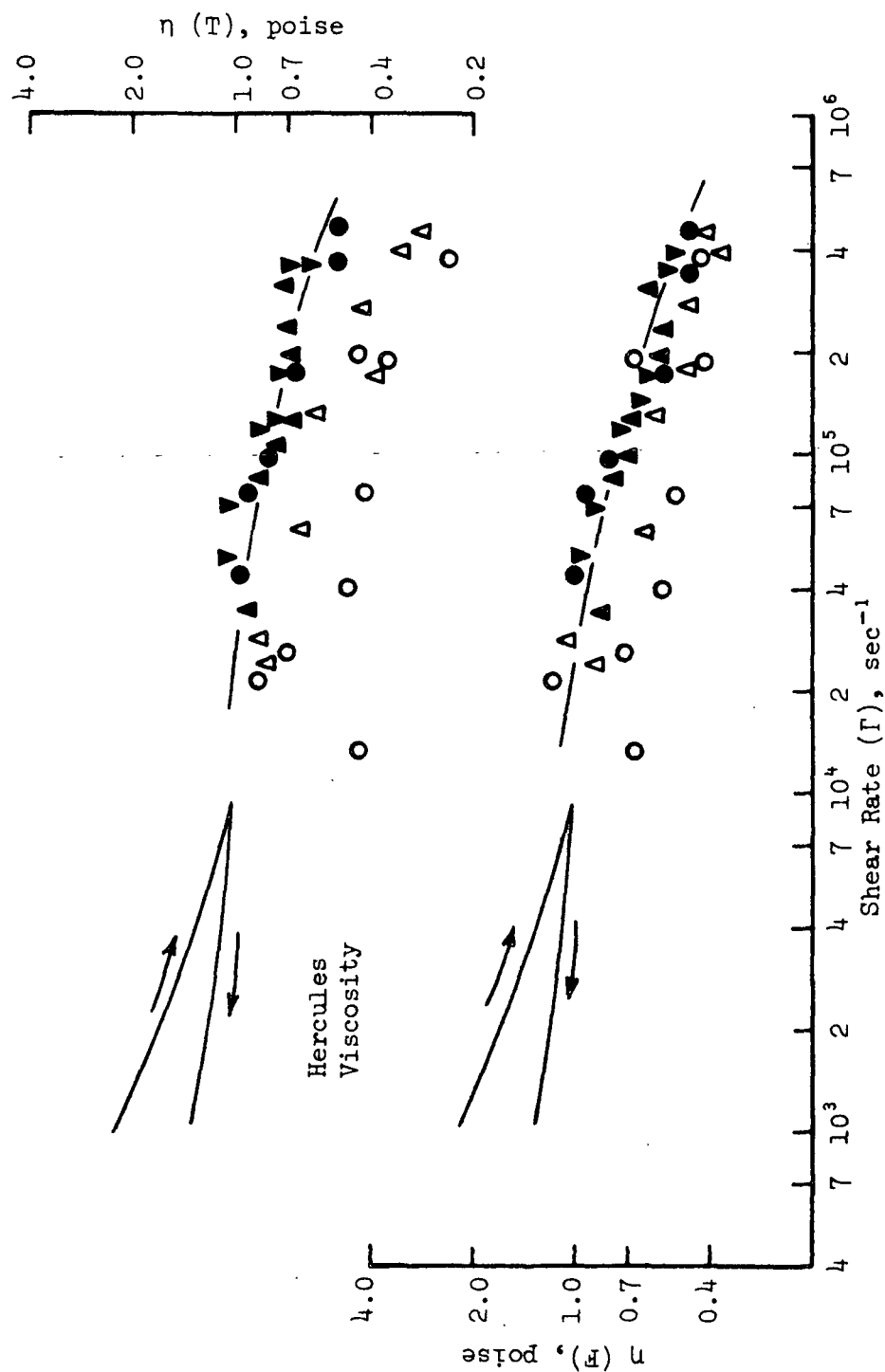


Figure 9. Viscosity Data for Coating No. 8. Key to Symbols Same as Fig. 8.
Volume Fraction of Clay Plus Latex: 0.362. 35°C

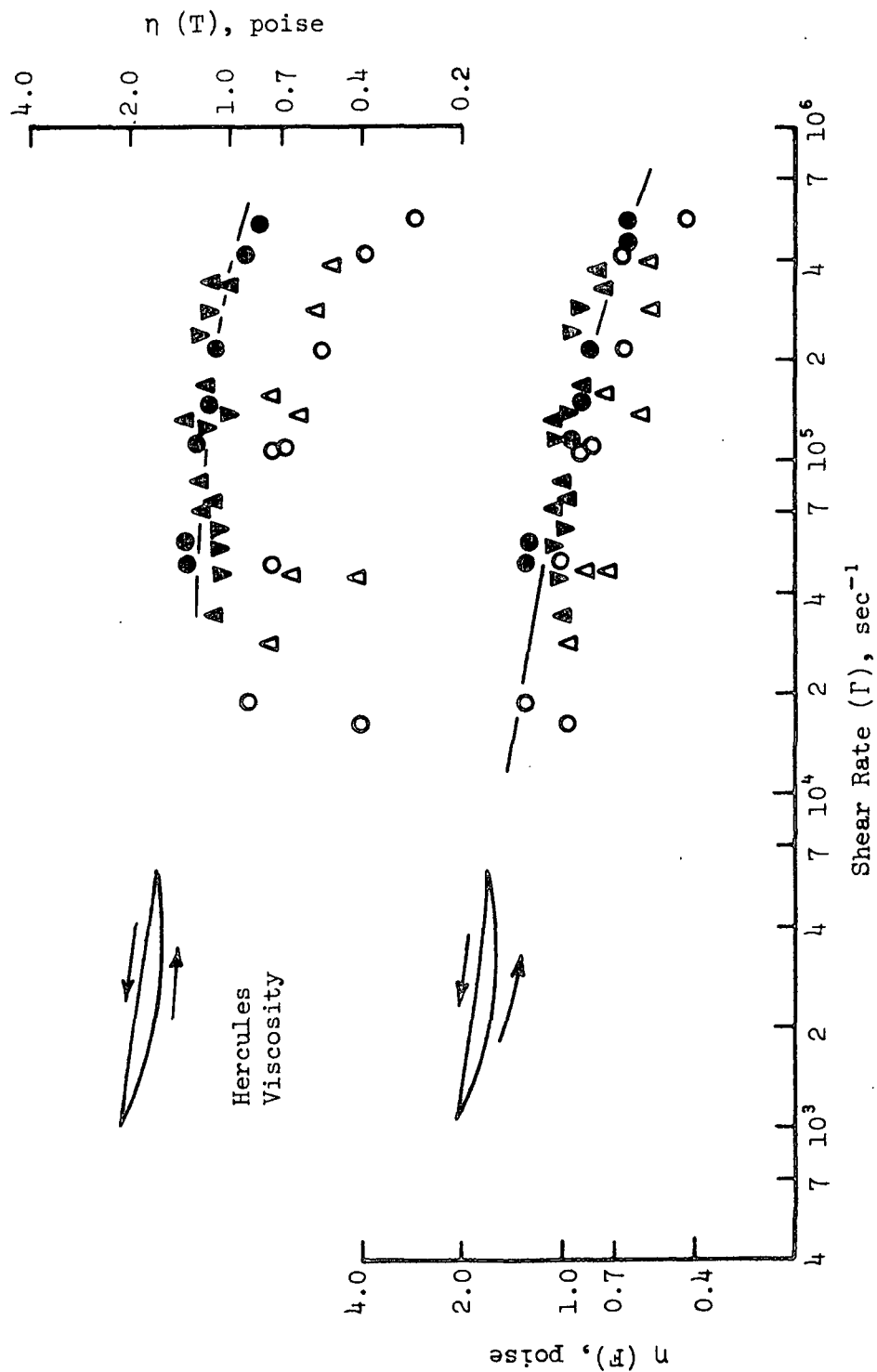


Figure 10. Viscosity Data for Coating No. 9. Key to Symbols Same as Fig. 8.
Volume Fraction of Clay Plus Latex: 0.439. 35°C

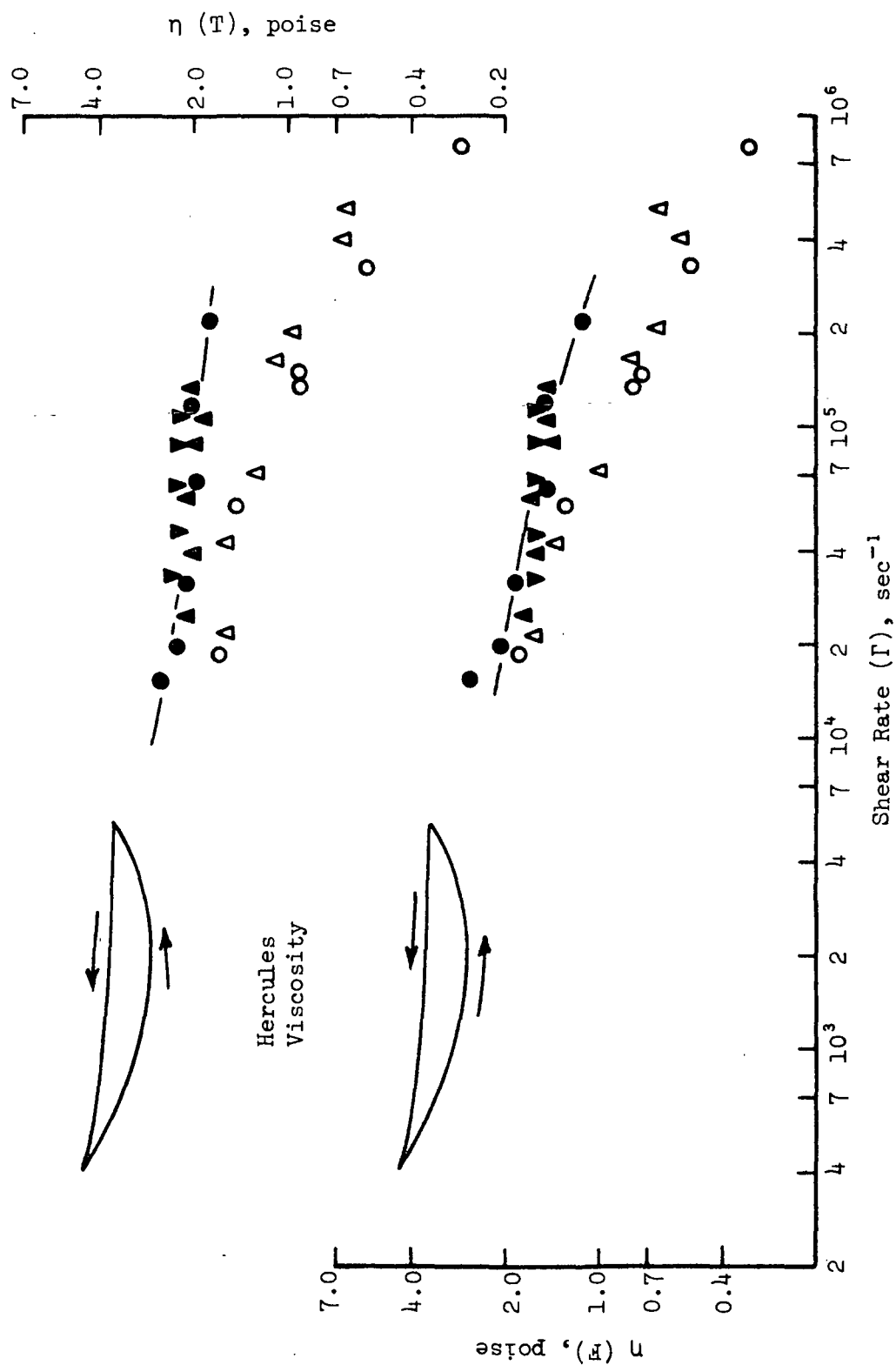


Figure 11. Viscosity Data for Coating No. 10. Key to Symbols, Same as Fig. 8.
Volume Fraction of Clay Plus Latex: 0.457. 35°C

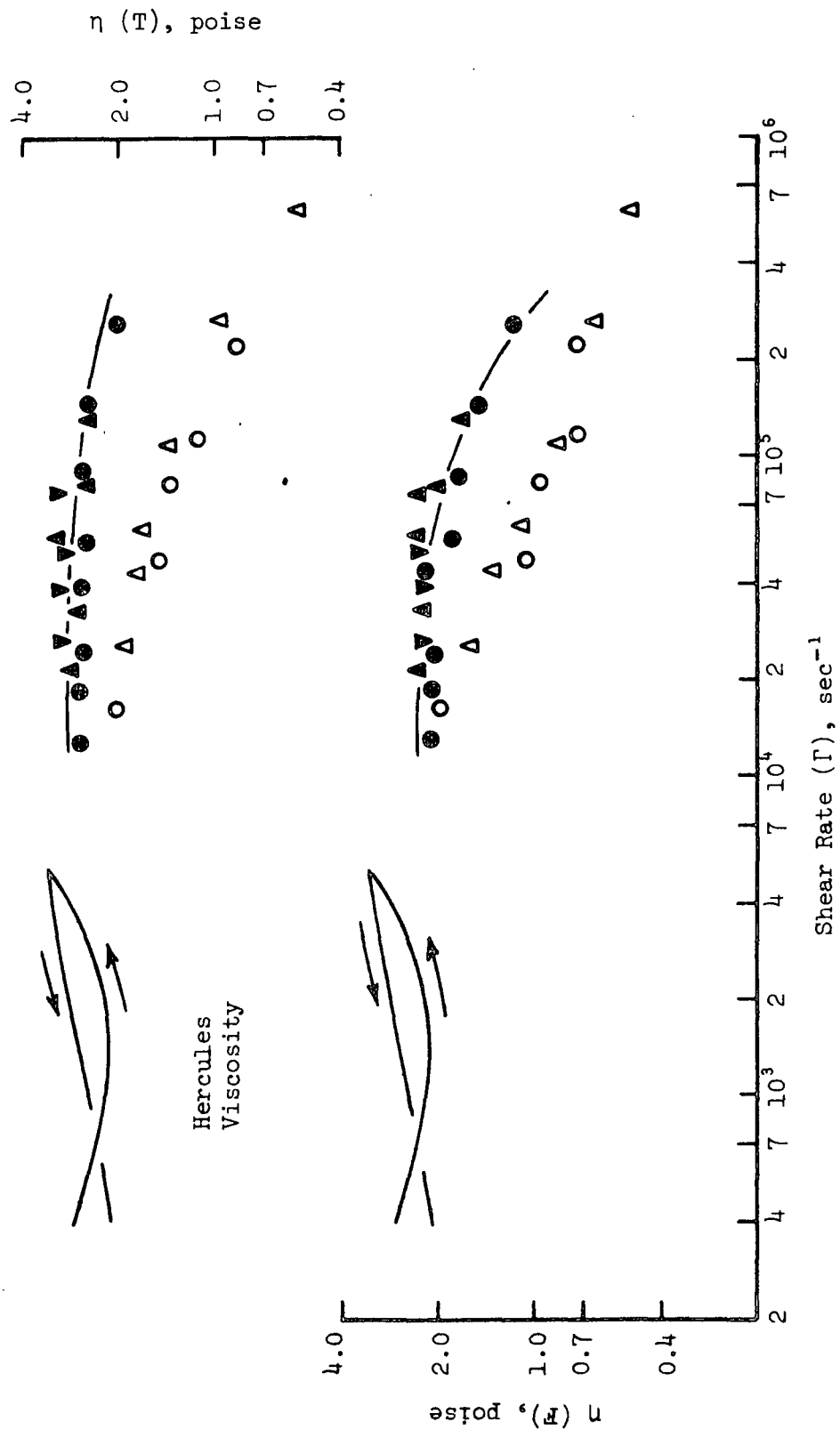


Figure 12. Viscosity Data for Coating No. 11. Key to Symbols Same as Fig. 8.
Volume Fraction of Clay Plus Latex: 0.484. 35°C

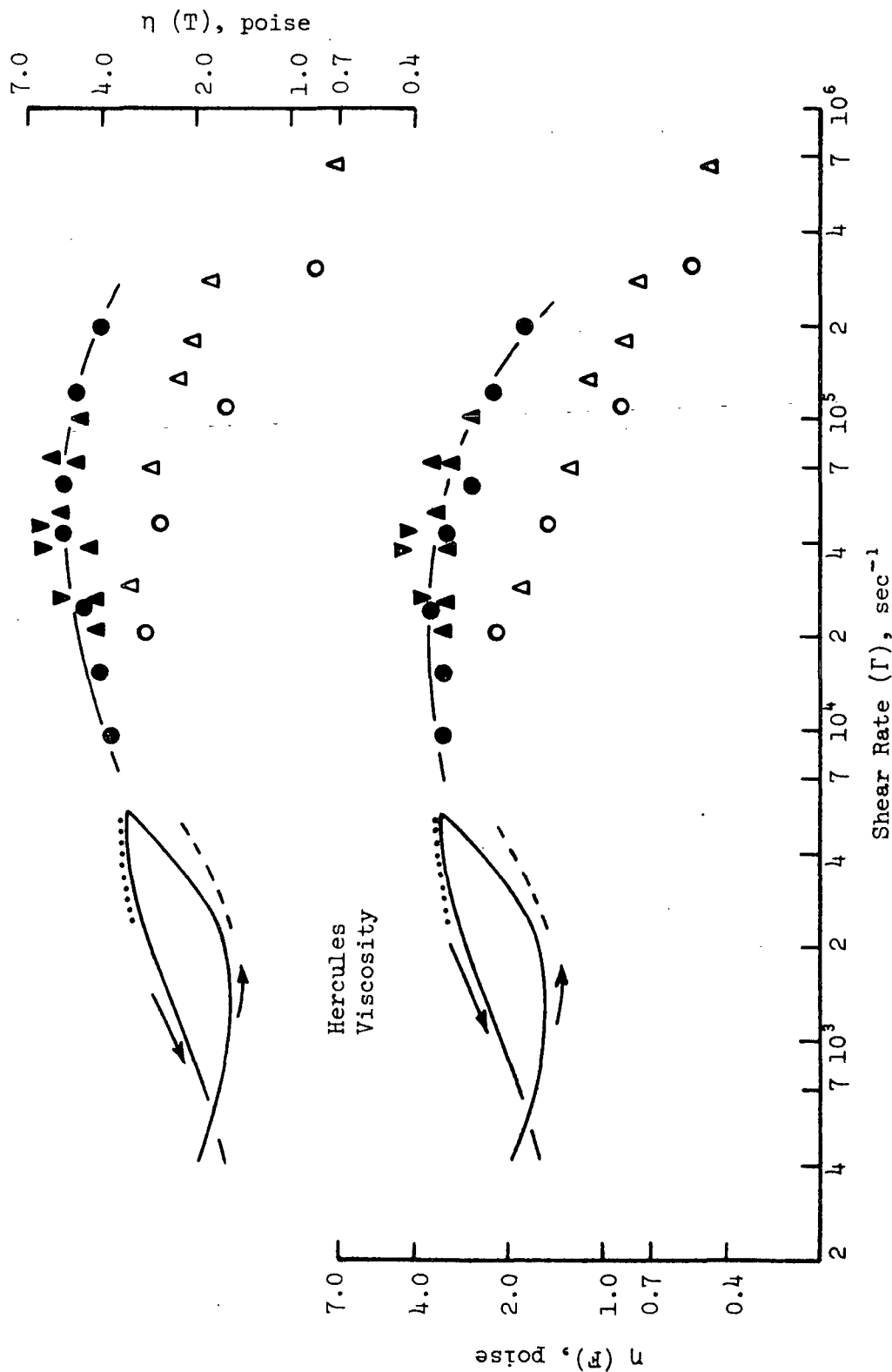


Figure 13. Viscosity Data for Coating No. 12. Key to Symbols Same as Fig. 8.
Volume Fraction of Clay Plus Latex: 0.506. 24°C

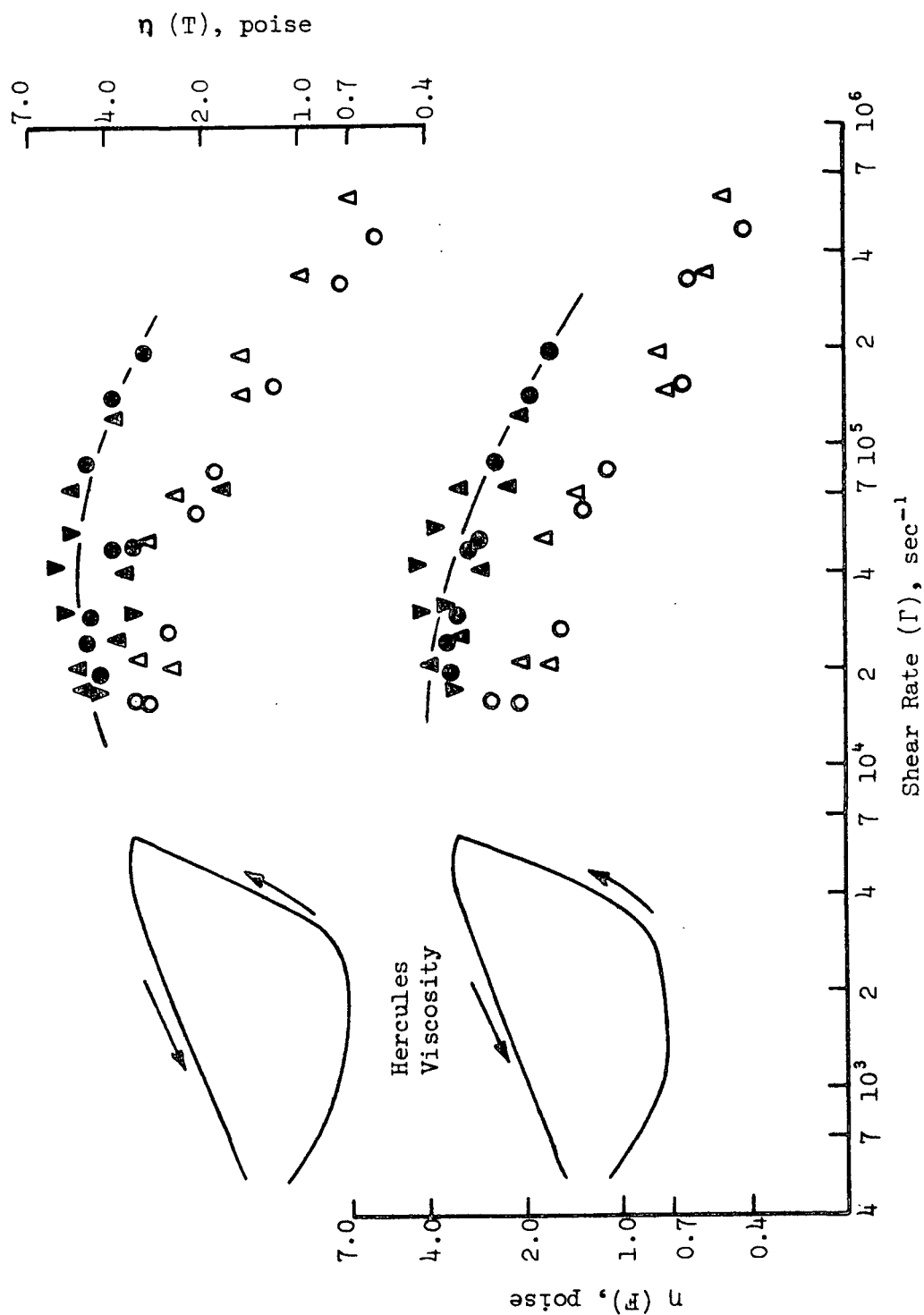


Figure 14. Viscosity Data for Coating No. 13. Key to Symbols Same as Fig. 8.
Volume Fraction of Clay Plus Latex: 0.511. 35°C

in the nip from zero to the maximum under the blade tip. The symbols on the figures correspond approximately to the maximum shear rate in each case. The maximum shear rate is that occurring under the blade tip at the outside radius of the blades. It may be approximated by $\omega R_o / \Delta$ in which ω is the rotational speed of the wear platen, R_o is the outside radius of the blades, and Δ is the separation distance between the blade tip and the wear plate surface. It is apparent that no reasonable straight line covers all of the data.

It would seem that deviations from viscometric flow should be more prevalent at high speed than at low speed, and the low speed results probably better approximate the true viscosity functions. For practical reasons, however, it is better to consider the high speed results to be the viscosities of interest since these speeds better approximate those attained on coating machines. Thus, if the high speed viscosities in Fig. 8-14 are in error due to deviations from the theory, it might be reasonable to expect that the error would in part cancel out in using the calculated viscosity functions and the same theory to predict behavior in coating nips.

The upper set of results in each figure is determined from torque (i.e., drag) and the lower set from normal force. The two sets of results generally differ some in quantity but not in form. Since the normal force results would correspond more closely to the viscosity function controlling coat weight, it is considered best to let the solid symbols in the lower set of data in each figure be the viscosity as determined by the rheometer.

The major observations to be made concerning the rheometer results are:

(a) In no case is the dilatancy which is observed with Hercules rheograms seen at the higher shear rates obtained with the rheometer. Instead Newtonian or even

shear thinning behavior is found. (b) There is no overlapping of results between the Hercules and rheometer viscosities, so direct comparisons are difficult to make. However, there does seem to be a reasonably good extrapolation from one to the other. (c) There is obviously greater scatter in data for the most dilatant coatings. The apparent reason for this will be seen later to be a result of the change in viscosity due to energy input to the coatings.

THE CONCEPT OF VISCOSITY DEPENDENCE ON BOTH SHEAR RATE AND ENERGY

Introductory Remarks

In the case of a thixotropic fluid it may be reasonably argued that there are two factors affecting the viscosity: the shear thinning effect in which viscosity is reduced as shear rate increases, and the reduction of viscosity due to structure breakdown. These two effects are suggested by the thixotropic loop characteristic of Hercules rheograms. By similar reasoning one might suggest two factors responsible for the viscosity of a dilatant suspension: true dilatancy in which viscosity increases with increase in shear rate, and an effect in which viscosity increases with a build up of structure.

This phenomenon is of more than idle interest since it affects significantly the methods of characterizing coating rheology, the interpretation of experimental data, and the application of test data to the coater.

Formulation of the Concept

A simple mathematical description of the concept is given by the following equation:

$$\eta = \eta (\dot{\Gamma}, E) \quad (1)$$

in which Γ is the shear rate, η is the viscosity, and E is the mechanical energy per fluid volume imparted to the fluid in the act of deforming it. The latter may be calculated from the following relationship:

$$E = \tau \Gamma t = \eta \Gamma^2 t \quad (2)$$

where τ is the shear stress and t is the time during which the fluid is undergoing shear. It is further suggested that there must be some limit to structure change due to energy effects so two limiting viscosity functions can be defined:

$$\eta(\Gamma, 0) = \text{zero energy viscosity function} \quad (3)$$

$$\eta(\Gamma, \infty) = \text{infinite energy viscosity function} \quad (4)$$

It is implied by Equation (1) that the viscosity is a unique function of energy at a given shear rate, regardless of the rate of energy application. Also, no provision is made for the reversal or recovery of structure with time. That is, it is presumed that there is no reversal or that the reversal time is long compared to the time scale for which Equation (1) is used. It might be desirable at some future time to incorporate some reversal factor in Equation (1). It is intended that Equations (1)-(4) apply to thixotropy as well as dilatancy.

Experimental Verification of the Concept

Two types of experiments were conducted on a coating with the Hercules Viscometer: (1) the usual rheograms were produced and (2) the viscosity was measured as a function of time with rotational speed held constant. At a given shear rate this led to three separate measures of viscosity as a function of energy input: the "up" curve of the rheograms has a rate of energy input history which starts at zero and reaches a maximum at the point of measurement, the

"down" curve of the rheograms has a rate of energy input history which goes from zero to a maximum and then decreases to the point of measurement, and a constant speed experiment has a rate of energy input history which is nearly constant to the point of measurement. On the "down" portion of a curve the total energy input at a given shear rate depends on the history of that particular run -- that is, upon the maximum shear rate at the start of the "down" curve. Hence a series of viscosities at a particular shear rate but with different amounts of input energy can be generated by stopping the "up" portion of the rheogram at different maximum shear rates and immediately beginning the "down" portion. In contrast there is only one point (viscosity) at a particular shear rate that can be obtained from the "up" portion of the curve, since there is only one pathway to this point. Four sets of data were obtained, with shear rate as the parameter, for the coating No. 12. The results are presented in Fig. 15. The lines through the data are "best fit" lines and have no theoretical significance.

Certain conclusions can be drawn from these results: (a) While the scatter of points is fairly large, it is seen that the points for the three energy input histories form reasonably coherent single curves. (b) The data lend some support to the presumed lack of structural reversal. More convincing observations were made in the course of the experiments. For example, in a repeated rheogram for a very dilatant coating, the "up" curve of the repeat was very close to the "down" curve of the first rheogram. As another test, the machine was stopped in a few of the constant speed experiments for periods of time of about 10-20 seconds. The torque on starting again was invariably about the same as it was on stopping, indicating little, if any, reversal. The possibility of increased torque caused by the formation of a skin on the coating due to evaporation limited these tests to relatively short times. (c) The data show the predicted tendency to level off at

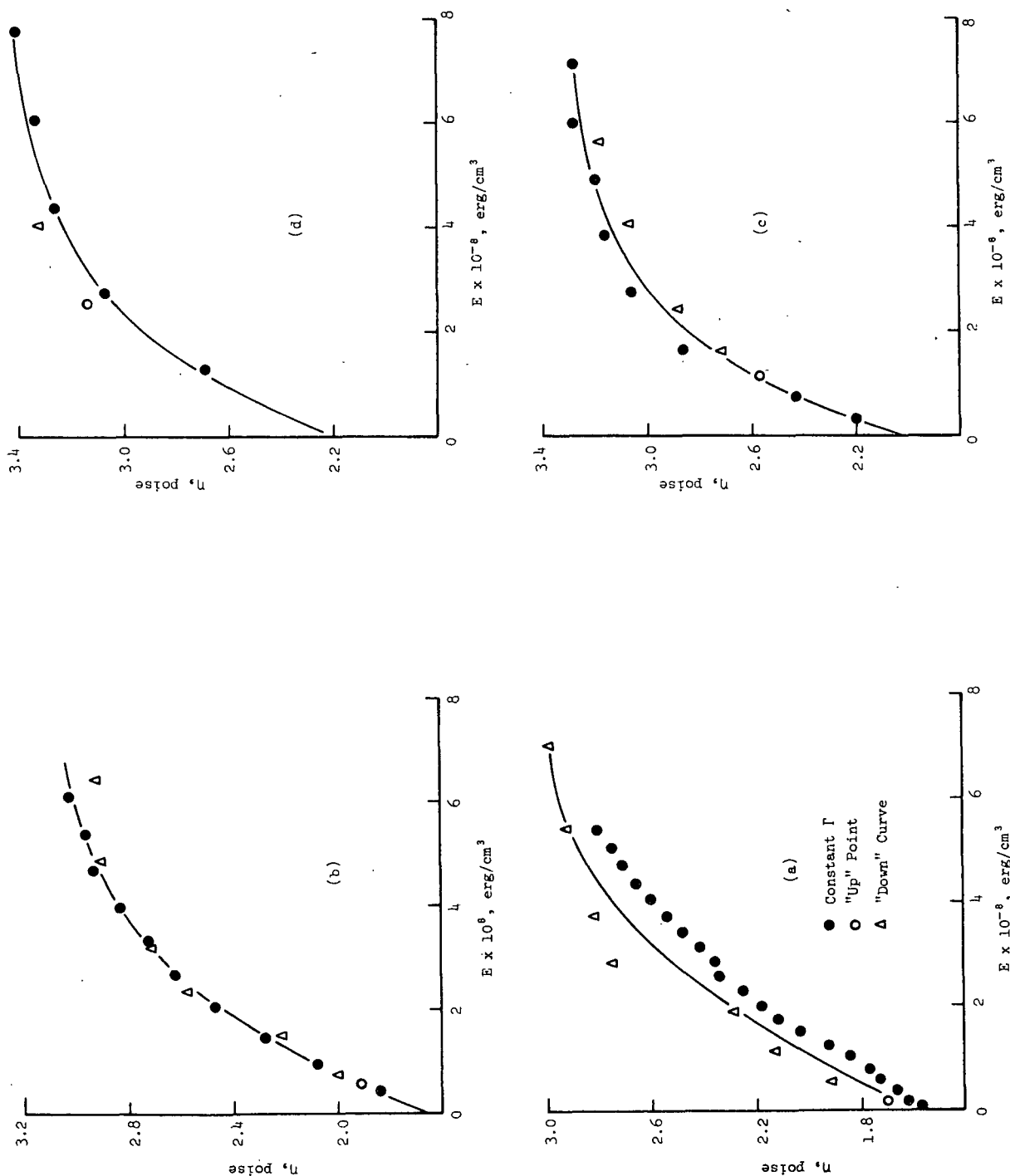


Figure 15. Hercules Viscosity as a Function of Input Energy Under Various Operating Conditions (See Text for Details) for Coating No. 12. Shear Rates:
(a) 2470, (b) 3360, (c) 4120, (d) 5060 sec⁻¹

high energy inputs. The evaporation problem mentioned above was the reason for not carrying the results even further in energy. It is of interest that the energy required to level off is about the same for each of the four shear rates considered.

Estimates of $\eta(\Gamma, 0)$ and $\eta(\Gamma, \infty)$ were made from the data of Fig. 15 and are plotted on Fig. 13 (the dots and dashes) to illustrate the viscosity envelope implied by Equations (1)-(4). The dashed line represents the estimate of the "zero energy" viscosity. It is apparent that the energy effect contributes strongly to the increasing dilatancy exhibited by this coating. The dotted lines indicate "infinite energy" viscosities. Evidently, the "down" portion of the rheogram is nearly equal to these values, another indication of the very slow reversibility of the structural change caused by the energy input.

The Interpretation of Rheometer Results in Light of the Shear Rate-Energy Concept

The question naturally arises: what part of the proposed viscosity envelope is being measured by the rheometer? At first it was considered probable that measurements were made close to the zero energy line since, on the average, a very large volume of fluid is absorbing the energy. However, considering the evident slow, or absent, reversal in energy effect mentioned before, the energy input might accumulate over the course of an experiment and be significant. In order to investigate this possibility the limited data available were used as follows: (a) Figure 15 contains the only results on the effect of energy input on viscosity. The four sets of data were of such similar shape that a single function was estimated and is given in Fig. 16. Here the vertical bars and the closed circles represent the extremes and the average, respectively, for the four shear rates. (The data can be well-fitted by an exponential function though the significance of this, if any, is not clear at present.) This gives the fractional

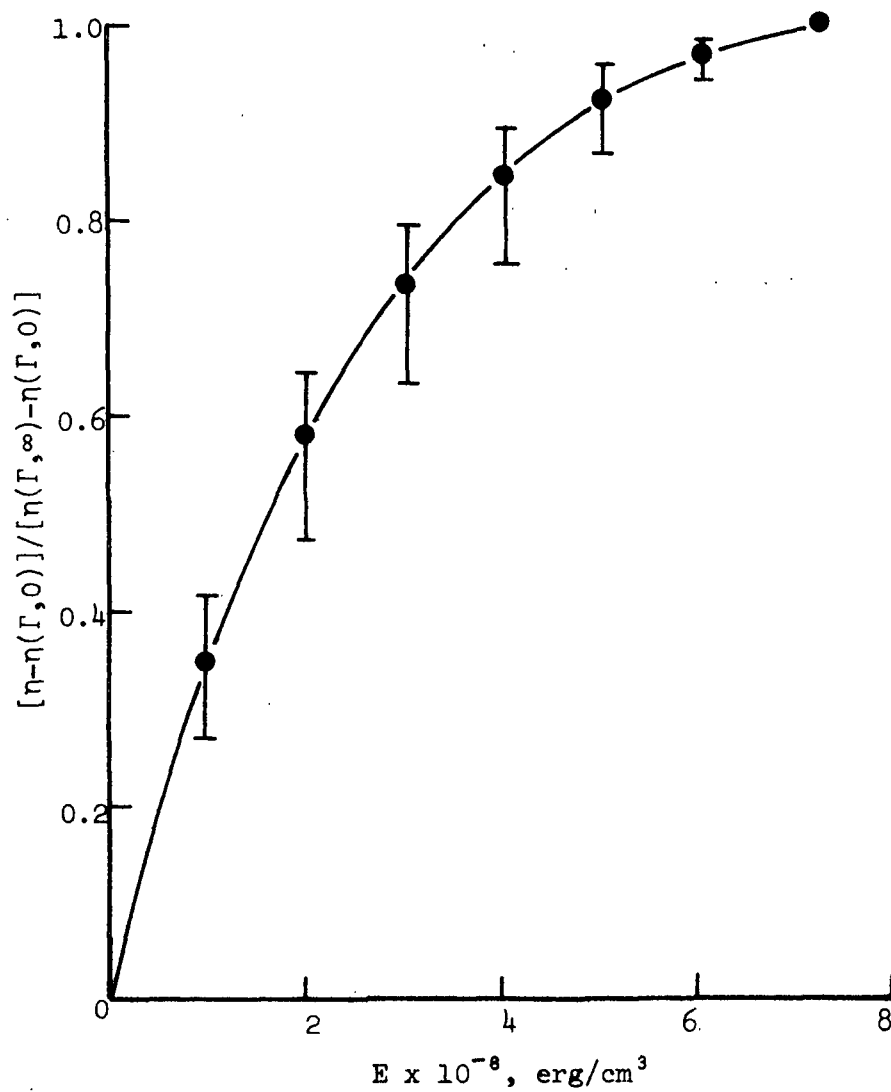


Figure 16. Reduction of Data from Fig. 15

distance from the zero energy viscosity to the infinite energy viscosity as a function of the energy input per fluid volume. (b) The experiment on coating No. 13 was the only one for which sufficient runs were repeated to permit a good check of the energy effect. It is assumed that the curve of Fig. 16, for the coating No. 12 is approximately that which would be obtained for coating No. 13 since the only difference between the two coatings was in temperature and a small difference in solids. (c) For the IPC Rheometer measurements on coating No. 13 it is estimated that 7.2 seconds of running time were required for each data set. The fluid volume was taken as 950 ml. These values were used in calculating the cumulative energy input to the coating, as follows:

$$\text{Energy/fluid volume} = \frac{(\text{torque}) \times (\text{rotational speed}) \times (\text{time})}{(\text{fluid volume})} \quad (4)$$

The calculated cumulative energy values were then used with the curve of Fig. 16 to estimate the fractional distance each point should be from the zero energy extreme to the infinite energy extreme. This fractional distance ranged from 0.2 to 0.9 for the various data points in Fig. 14 with no systematic trends with either shear rate or angular velocity.

The following conclusions can be drawn from these calculations: (a) There is indeed a significant effect of energy input on the viscosity results. The results apparently cover most of the viscosity envelope. (b) This suggests that the reversal time must be very large since at least one minute was allowed for rest between the taking of the sets of data. (c) This phenomenon is probably the major cause of the large scatter of data for the more dilatant coatings.

One additional observation might be of interest and significance here. It was observed at the end of the experiments that a line of coating which was difficult to remove accumulated on the edge of the wear plate near the bottom. This area was under the surface during the experiment and could not have dried by evaporation. While this area is outside the regions of high shear it is possible that coating moves from the regions of high shear by centrifugal force and is deposited here. In any case it suggests that a comparable effect occurring in a coater could lead to deposits of nonfluid coating at various points in the coater, resulting from action in the coating nip, and not related to evaporation.

RELEVANCE OF THE EXPERIMENTAL RESULTS TO COATING OPERATIONS

Consideration should be given to what, if any, advantages might be gained by using coatings which are normally considered to be dilatant. The primary point to be made is that this could permit an increase in coat weight due to higher effective viscosity at high shear rates without increase in low shear viscosity and the corresponding increase in coating handling problems. It has been shown that even the most highly dilatant coatings (by Hercules Viscometer standards) are slightly shear thinning as tested at the high shear rates in the IPC Rheometer. It might be possible, then, to take advantage of these coating properties, without introducing the blade scratching which is considered characteristic of dilatant coatings.

However, caution should be exercised. For example, an all latex binder coating might have the desired high effective viscosity at high shear rate but be very fluid at low shear. If the coating were too fluid at low shear, too much water might migrate into the sheet prior to the nip. This would result in a solids increase and a much higher viscosity than desired in the nip, perhaps even dilatancy at high shear rate.

Another point to be considered is the effect of long dwell times in the nip. Coating which passes straight through the nip probably is near the zero energy viscosity. Recycled coating or coating near the high shear static line (see Appendix IV, Progress Report One) may be increased to the infinite energy viscosity and perhaps lead to nonfluid coating deposits similar to those observed in the rheometer tests. These deposits might get in the coating and serve as scratching particles.

PROJECT SUMMARY

During the course of this project rheological characterization of coatings has been achieved up to shear rates of 10^5 to 10^6 sec^{-1} . This represents at least an order of magnitude increase compared with the usual Hercules or Ferranti-Shirley viscometers. The utility of the instrument has been shown especially for the more complex coating formulations. For these, rheological predictions for typical coater operation speeds by extrapolation from lower shear rates would give erroneous results.


By using viscometer configurations such that a series of blades are the shearing elements, the validity of the usual assumption of viscometric flow in blade nips has been tested. It was found that the assumption was applicable for simple systems (clay/starch coatings) at low (10°) blade angle. However, for viscoelastic or dilatant coatings at all blade angles and for simple systems at high (45°) blade angle, nonviscometric flow exists. It is not surprising that the flow is nonviscometric in the converging entrance to the blade nip. Strong contributions from elongational flow are predicted and found for polymer solutions in similar flow geometries. A mathematical model has been devised for computer solution of the nonviscometric flow. It has not been tested sufficiently to assess its adequacy in describing real flow in the blade geometry.


Since the flow in a system similar to a typical coater operation has been shown to be nonviscometric, the unreliability of predicting coating behavior from measurements made in simple shearing flow at low shear rates is apparent. It is anticipated that further advances in the understanding of coating rheology will only come via further measurements in the realm of high shear rates and nonviscometric flow geometry and with the development of an adequate mathematical description of such flows.

LITERATURE CITED


1. Ginn, R. F. A fundamental rheological study of the blade coating process. Project 3069, Progress Report One, The Institute of Paper Chemistry, July 27, 1973.
2. Ginn, R. F. A fundamental rheological study of the blade coating process. Project 3069, Progress Report Two, The Institute of Paper Chemistry, August 9, 1974.
3. Ginn, R. F. A fundamental rheological study of the blade coating process. Project 3069, Progress Report Three, The Institute of Paper Chemistry, May 16, 1975.
4. Personal communication from G. D. Miller of the Air Products Co.
5. Miller, G. D. and Kennedy, H. M. PVOH as a coating color binder. Chem 26, Paper Processing 8(10):32(1972).
6. Ferry, J. D. Viscoelastic properties of polymers, 2nd ed., Wiley, New York, 1970.

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APPENDIX I
COMPUTER PROGRAMS

RHEOM

Description

This is a program describing the flow of fluids in nips of any geometry. Fluid properties are limited only to having viscosity and viscoelastic normal stresses being power law functions of shear rate. The theory is limited by the assumption of viscometric flow in the nip. The output includes velocity, deformation, and stress profiles as options. The major outputs are the normal force and drag force exerted by the fluid in the nip.

Status

The program is described by included comment cards. The program is available to sponsoring companies on cards or tape, or a listing of the program can be provided.

RHEOM RESULTS CONVERSION PROGRAM

Description

This program converts results from RHEOM to a more useful form and punches them out on cards. These converted results are then used as part of the IPC RHEOMETER RESULTS program described below.

Status

The program is described by included comment cards. The program is available to sponsoring companies but is of use only in preparing the following program to analyze IPC Rheometer data.

IPC RHEOMETER RESULTS PROGRAM

Description

This program converts experimental data from the IPC Rheometer to coating viscosity results (under the viscometric flow assumption).

Status

The program is described in included comment cards. It is available on request but presumably would be of little interest except in analyzing Rheometer data.

REVISED THEORY PROGRAM

Description

This is a computer model of flow in the blade nip which does not depend on the assumption of viscometric flow, as was true of the first model (RHEOM). While the program is in working order it has not been sufficiently tested to determine what ranges of input variables can be handled. Some trouble was encountered under conditions such that inertial forces became comparable with viscous forces. Very little testing was done with viscoelastic fluid properties as input, so the potential there is uncertain.

Status

The program is described in a set of notes. On request the notes and a listing of the program are available to sponsoring companies. The program on cards or tape is also available.

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